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Sustainable Concrete Design Using Brown Chicken Eggshell to Reduce Carbon Footprint

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Abstract - The construction industry, as well as the food industry, are two influential sectors in the economy of Peru. However, processes such as cement manufacturing for use in concrete production and the disposal of food waste are two of the main causes of environmental pollution globally. This research considers the use of brown chicken eggshell, typically considered waste in the food industry, to be used as a partial replacement for cement in concrete mixes. The experimental work conducted analyses the properties of concrete in a hardened state through destructive and non-destructive laboratory tests, evaluates the effectiveness of eggshell as a partial replacement for cement in three presentations: fresh eggshell, dried eggshell, and eggshell ash; and determines the variation in carbon footprint of the concrete with eggshell compared to the standard concrete mix. This sustainable approach not only improves the properties of concrete but also marks an important step towards sustainable construction and the reuse of food waste.

Keywords**:** sustainable constructions, sustainable material, concrete mix, eggshells, concrete, carbon footprint

1. Introduction

In Peru, environmental pollution is one of the most serious problems and has serious consequences for the health of the population. Currently, our country faces the challenge of having the most polluted air of all Latin American countries [1]. This situation is mainly due to two large industries: construction and food.

On the one hand, the growth of the construction industry is reflected by the impact it has on the country's economy. This sector contributes 6.7% to the Gross Domestic Product (GDP) of Peru [2]. With its growth, the demand for cement-based materials increases, the manufacture and use of which contribute to 8% of global CO2 emissions [3]. On the other hand, the food industry is also an important driver of the Industrial Gross Domestic Product (GDP), contributing 36.7% [4]. However, it generates food waste of 12.8 million tons annually in Peru alone [5] and 931 million tons globally [6].

The increase in industrial and poultry waste hurts the environment, motivating the search for ecological alternatives by scholars and specialists. Among the alternatives is the use of alternative materials to cement. Global research supports the benefits of replacing cement with waste materials. Waste materials have two categories: industrial and poultry origin. Studies prove that industrial byproducts such as fly ash [7] and volcanic pozzolans [8] have managed to substantially improve the properties of cementitious materials. Poultry byproducts such as eggshells also present such benefits, with the addition that their use in concrete develops synergistic effects where the benefit is mutual, both for construction companies and society as a whole, because they are reusing zero-cost poultry waste, giving it a new social and ecological value in the construction industry [3].

Regarding the production of this waste, of poultry origin, in the year 2000, 55 million tons were produced and by 2018 it increased to 83 million tons [3]. The shells have valuable amounts of calcium in the form of calcium oxide and calcium carbonate, making them a partial substitute for cement in building materials [9].

The use of eggshells as a partial replacement for cement for the manufacture of concrete is a promising solution to reduce its carbon footprint of 10,095 kg CO2/kg. Several investigations have been conducted on the use of chicken eggshell powder as a partial replacement of cement in concrete mixes [10], cement mortar [11], concrete blocks, and pavers [9]. However, these use eggshell directly at calcined temperatures around 700-800°C, since the calcium present in the eggshell, when thermally activated, is converted into oxides that can replace cement [10]. To date, no comparative studies have been carried out that analyze the impact of eggshells at different temperatures on the properties of concrete in the fresh state and its compressive strength in the hardened state. This area of research is crucial to understanding how thermal variations in eggshells can affect concrete characteristics and exploring possible sustainable applications of these alternative materials.

Since the results of previous research do not yet provide definitive conclusions, the purpose of this study is to develop concrete mixtures that incorporate chicken eggshells, comparing their specific properties to determine which option between fresh eggshell (CF), eggshell dried egg (CS) and eggshell ash (EC) is optimal to be used in civil construction projects. On the other hand, environmental problems linked to concrete, cement, and poultry waste are addressed, promoting the development of more sustainable alternatives in two industries with accelerated growth worldwide: construction and food.

2. Materials and methods

The present investigation is experimental. An evaluation and monitoring are carried out through laboratory tests on different concrete designs, for which some study variables are established, such as the water/cement ratio, cooking temperature of chicken eggshells, and percentage of calcium oxide, compressive strength of concrete mixtures, and the carbon footprint emission factor.

Within the proposal that considers the use of eggshells, three types of material are evaluated: fresh shell (CF) at 23°C, dry shell (CS), and ash (CE). These last two were cooked and incinerated in an oven at temperatures of 110°C and 800°C respectively.

Initially, a chemical analysis is carried out on the three eggshell samples to obtain their percentages of calcium oxide and moisture. Subsequently, NTP 400.018 [12] is used to evaluate the 200 mesh throughput in the aggregates, NTP 400.012 to carry out the granulometric analysis of fine and coarse aggregate [13], NTP 400.022 to carry out the weight test specific gravity and absorption of coarse sand [14], NTP 400.021 is used to evaluate the specific weight and absorption of gravel [15], and NTP 339.185 [16] used to measure moisture content.

For the design of the concrete mix, the ACI standard 211.1[17] is followed using the fineness modulus method. Subsequently, specific tests are carried out such as NTP 339.035 to evaluate the slump in concrete [18], NTP 339.083 to measure the air content in concrete [19], NTP 339.046 to determine the unit weight in concrete [20], and NTP 339.184 to evaluate the temperature in particular [21].

To analyze the properties of eggshells as a component of concrete, four types of mixtures are designed using the fineness modulus method. They were called: master mixture (PA), mixture with fresh eggshells (CF), mixture with dried eggshells (CS), and mixture with eggshell ash (CE). In all these mixtures, 10% eggshell is incorporated by the weight of the cement. Previous research indicates that replacing 10 to 15% of the cement with eggshell ash provides strength comparable to the control group [3]. 10% was chosen as a standard to compare the mixtures made.

Tests are then carried out on the concrete in its fresh and hardened states to evaluate the mechanical properties. Finally, the environmental performance is evaluated by comparing the calculation of the carbon footprint of the eggshell mixture with the best properties against that of the master concrete.

The results obtained in this study provide a robust basis for future research in the field of sustainable construction. In addition, they represent significant progress towards reducing pollution derived from the construction industry and reusing waste from the food industry.

3. Results and discussion

The quantitative results of this research are presented below.

3.1. Determination of aggregate properties

To carry out the concrete mix design, tests are previously applied to the materials to know their properties. First, the granulometric analysis of gravel and coarse sand is carried out considering the percentage limits of the retained weight as seen in figures 1a and 1b.

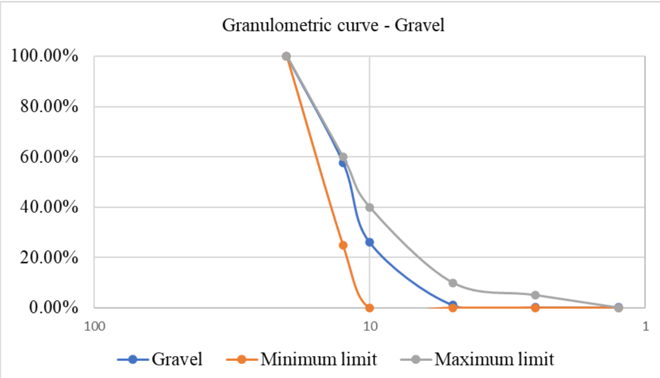

Fig. 1a: Granulometric curve of gravel

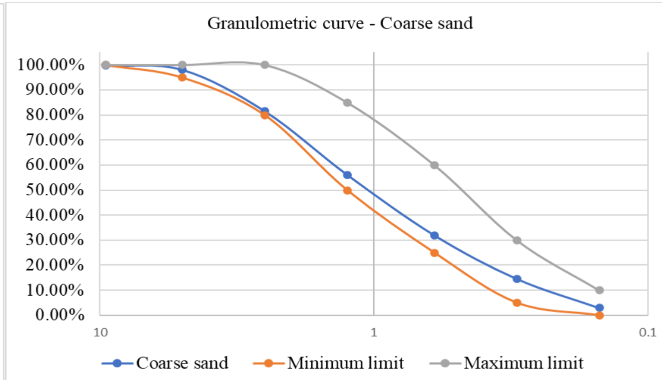

Fig. 1b: Granulometric curve of coarse sand

Afterwards, specific weight, absorption and moisture content tests are carried out. These tests are subjected to gravel and coarsed sand. The results of the aggregate tests are in Table 1.

Table 1: Aggregate test results

Property	Unit	Coarsed sand	Gravel
% mesh 200	%	4.96	0.32
Specific weight	kg/m3	2614.37	2820.07
Absorption	%	0.91	2.00
% Moisture	%	0.88	1.24

3.2. Chemical analysis of CF, CS and CE eggshells

The chemical analysis carried out on the different eggshell samples shows the percentage of calcium oxide and moisture as seen in Table 2.

Table 2: Results of chemical analysis on eggshell samples

Sample	Moisture (%)	Calcium oxide (%)
CF	2.32	6.31
CS	0.81	9.69
CE	0.30	36.65

3.3. Concrete mix design

Table 3: Proportioning Eggshell Concrete Designs

Materials	Unit	PA	CF	CS	CE
Eggshell ash	kg	0	0	0	39
Fresh eggshell	kg	0	39	0	0
Dried eggshell	kg	0	0	39	0
Cement	kg	393	354	354	354
Coarsed sand	kg	888	888	888	888
Gravel	kg	807	807	807	807
Water	L	223	223	223	223

The mix design is carried out using the fineness modulus method with the ACI 211.1 tables [17], with a f'c of 280 kg/cm2 and a slump of 3”. Mixture designs are made with 10% for fresh eggshell (Sample CF), dried eggshell (Sample CS) and eggshell ash (Sample CE), and without additions for the standard mixture (Sample PA). The final designs are shown in Table 3.

3.4. Determination of properties of the concrete mixture in the fresh and hardened state

The results are shown in Tables 4 and 5.

Table 4: Test results on fresh concrete

	Unit	CF	CS	CE	PA
Temperature	°C	23.6°C	24.7°C	23.9°C	24.1°C
Slump	in	1/4"	1/2"	1/2"	1/2"
PU	Kg/m3	2246.78	2280.01	2330.58	2324.80
Air content	%	2.85%	3.20%	3%	3.10%

Table 5: Results of the compression test on cylindrical specimens

Mix	Age (days)	P (Kn)	Diameter (cm)	Height (cm)	F´c (kg/cm2)
PA	7	226.23	10,00	20	293.62
CF		183.01	10,06	20	237.53
CS		196.23	10,09	20	254.69
CE		202.30	10,07	20	262.57
PA	14	233.23	10,00	20	302.71
CF		197.39	10,00	20	256.19
CS		198.70	10,00	20	257.89
CE		239.10	10,01	20	310.33
PA	28	241.87	10.04	20	313.93
CF		201.39	10.06	20	258.16
CS		202.51	10.09	20	262.84
CE		251.40	10.09	20	326.29

Based on the results, it is shown that the mixture design with eggshell ash (CE) has the highest compressive strength at 28 days.

3.5. Evaluation of the carbon footprint of concrete

The carbon footprint is evaluated for the master mixture (PA) and for the mixture with eggshell ash (CE). The results are shown in table 6.

Based on the results, a carbon footprint reduction of 6.05% was obtained for sustainable concrete with eggshell ash compared to standard concrete (PA).

Table 6: Results of the carbon footprint calculation in the master mix design (PA) and with eggshell ash (CE) for the preparation of one cubic meter of concrete

Class	**Detailed Content**	**Emission factor (Kg CO2/Kg)**	**Sample PA**		**Sample CE**	
			Consumption (Kg)	Carbon footprint (Kg CO2)	Consumption (Kg)	Carbon footprint (Kg CO2)
Materials	Eggshell ash	0.288	0	0	39.38	11.342
	Portland Cement Type I	0.758	393.83	298.522	354.45	268.670
	Coarsed sand	0.002	888.55	1.777	888.56	1.777
	Water	-	222.89	0.000	222.89	0.000
	Gravel	0.007	807.22	5.651	807.22	5.651
Transport	Material transportation	0.00261	0	0	0	0
Production	Sifting	-	0	0	0	0
	Materials mix	-	0	0	0	0
	Molding of the mixture	-	0	0	0	0
	Cured	-	0	0	0	0
Total				305.949		287.440

4. Conclusion

Mixtures with eggshell (CF, CS, CE) show compressive strengths comparable to standard concrete at different stages (7, 21, and 28 days). The CE mixture, which incorporates chicken eggshell ash, stands out by consistently showing the highest compressive strength in crucial periods of 7, 14, and 28 days. Likewise, eggshell ash shows that it has a calcium oxide percentage of 36.65%. This phenomenon supports the effectiveness of replacing 10% of cement with eggshells, achieving the desired strength in concrete mixtures. The consistency in performance suggests that eggshell ash plays a critical role in improving the physical properties of concrete, ensuring robust performance over time.

Carbon footprint analysis reveals a significant 6.05% reduction in the carbon footprint of eggshell ash concrete compared to master concrete. Incorporating eggshells, especially in their ash form, not only improves physical properties but also contributes substantially to environmental sustainability in construction.

In conclusion, the research supports the feasibility and effectiveness of chicken eggshells in the ash state (CE) as a partial substitute for cement in concrete mixtures. The increase in compressive strength and a significant reduction in carbon footprint highlight the promising prospects of eggshells as a sustainable resource in construction. These findings not only suggest an improvement in concrete properties but also offer a practical solution to address the environmental challenges associated with construction. The integration of eggshells into construction practices could represent a significant step towards creating more resistant and environmentally friendly structures. In this way, sustainable constructions will be able to increase worldwide and contribute to stronger synergistic effects between business and society in caring for the environment.

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